EXPERIMENTAL STUDIES OF STRESS-STRAIN BEHAVIOUR OF EPOXY AT HIGH STRAIN RATES

A Thesis Submitted
in Partial Fulfilment of the Requirements
for the Degree of

MASTER OF TECHNOLOGY

By

V. S. CHIMMALGI

to the

DEPARTMENT OF MECHANICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY, KANPUR

AUGUST, 1981

CERTIFICATE

This is to certify that the thesis entitled "Experimental studies of stress strain behaviour of epoxy at high strain rates", by V. S. Chimmalgi is a record of work carried out under my supervision and has not been submitted elsewhere for a degree.

Prashant Kumar

(PRASHANT KUMAR)
ASSISTANT PROFESSOR
DEPT. OF MECH. ENGG.
I.I.T., KANPUR

ACKNOWLEDGEMENTS

I wish to express my deep sense of gratitude to Dr. P. Kumar for his valuable and encouraging guidance at every phase of this work.

I am very much indebted to Mr. D.K. Sarkar and R.K. Nakrani for their help given in conducting the experiments. I thank Mr. L.J. Rao and Mr. B.Patro who were always ready to help me. I also thank Mr. S.L. Srivastava, S. N. Yadav, R.S. Shukla, U.S. Tiwari, C.P. Sechan, K. Banerjee, S.J. Hasnain for their help to me.

I am greatful to Mr. B.L. Sharma for his careful and accurate fabrication of Air-gun and its accessories.

I finally thank Mr. D.P. Saini for his excellent typing.

V.S. CHIMALGI

CONTENTS

LIST OF FIGURES

LIST OF FIGURES

ABSTRACT

Kolsky pressure bar setup is designed, fabricated and tested for its working. An Air-gun of 20 mm bore is perfected along with accessories such as low rise time strain gauge circuit, triggering device etc. The technique is used to determine stress strain curve of materials at high rate of deformation.

An application of the Kolsky technique to determine stress strain curves at high strain rate on the CY 230 epoxy material is given. A short specimen is sandwiched between two elastic bars and is loaded by a single stress pulse of 115 microseconds duration, propagating through the bars. Incident, transmitted and reflected pulse are recorded through strain gauges on pressure bars, with the help of a storage oscilloscope. Strain rates range from 920 sec^{-1} to 1450 sec^{-1}. Stress vs. strain curves at high strain rates are compared with a quasi static curve. The results indicate that the CY 230 epoxy is highly strain rate sensitive.

CHAPTER - I

INTRODUCTION

The mechanical behaviour of many metallic and non-metallic substances has been known to be affected by the rate of deformation. For example, 1100-0 Aluminium shows 75% increase in its strength under a strain rate of $2.6 \times 10^{3}\ sec^{-1}$ [13*]. Therefore, the study of dynamic behaviour of materials is important from several point of views, such as fabrication, cutting, failure criterion, strength and mode of failures etc. For example, in deep drawing where material deforms at a high rate, one should know how much additional load is required due to higher stresses. Another example can be of few investigators[2] studying machining process at high strain rates. Further more during collisions, material is stronger than what is predicted by the conventional tests; an Aeroplane body can with stand high contact stresses when a large bird impacts its body.

Measurement of dynamic stress-strain behaviour is a difficult problem. The conventional type of material testing machines such as Instron can produce a maximum strain rate of the order of $10^{-2}\ sec^{-1}$. Therefore unconventional methods have to be devised for study at high strain rates of the order of $10^{3}\ sec^{-1}$.

For the first time, Kolsky[11] in 1949 measured material properties at high strain rates. He compressed a short piece of specimen

---

* Gives the reference number

between two long, hard and elastic bars of circular cross section. He named the technique after Hopkinson[4] and called it Split-Hopkinson bar. Hopkinson was the first person to study waves in a bar, but he never designed to measure material properties. The technique has been accepted very well throughout the world in the last thirty years and recently, investigators[9] have started calling it as Kolsky Pressure Bar Technique. In the technique the specimen is loaded by a single pulse travelling through the pressure bars. Detonator was used to give velocity to a striker bar, which is short in length compared to the pressure bars. The striker bar impactsthe free end of the pressure bar generating a transient stress wave propagating through the pressure bars and the specimen. The pressure bars used, serve both as loading medium as well as transducers. Kolsky used a cylindrical condensor microphone fixed over the pressure bars for strain measurements. Also, Kolsky introduced a very simple data processing method to obtain a relation between average stress and average strain.

Davies and Haunter[3] (1963) used Kolsky bar to determine the behaviour of some metals, like annealed Cu, Al, Mg and some Polymers. He used compressive loading pulses of duration 30 microseconds. Lindholm and Yeakley[13] (1968) extended the Kolsky technique for obtaining complete stress-strain curves at strain rate of 1000 sec^{-1}. Thus they were able to determine the properties of Aluminium in both tension and compression modes.

Dharan and Hauser[4] (1970) reported stress-strain relation of compression test on Aluminium at strain rates from 4000 sec^{-1} to 120,000 sec^{-1}. Although they made corrections for lateral inertia, while the data to obtain strain rates as high as 120,000 sec^{-1} in uniaxial stress mode is questionable.

The Kolsky technique has been used by many investigators, only with slight changes such as using strain gauges for measuring strains. It is,therefore not possible to mention all tests conducted so far.

Duffy, Campbell and Hawley[5] (1971) modified the technique to torsional method in which a torsional pulse instead of compression pulse is passed through a specimen. The torsional pulse was generated by the simultaneous detonation of two explosive charges and the pulse was smoothened by using a pulse smoother. The mechanical behaviour of the material (stress-strain curve) was directly obtained on oscilloscope screens by using operational amplifiers and integrating circuits.

Jahsman[9] (1971) has applied a one dimensional elastic wave propagation analysis to assess the validity of the Kolsky formulas for measuring dynamic material behaviour. He showed that when one dimensional effects dominate, by careful selection of design parameters, such as specimen length and pulse shape one may use the Kolsky formulae with confidence.

Amijma Sadao and Toru Fujii[16] (1976) have conducted experiments on glass fibre reinforced composite materials. They prepared the

specimen by laying glass fibre cloth sheets parallel to each other in epoxy matrix. Strength of such composites increases with increase in strain rate and with increase in volume fraction. However, they did not look into the reasons of high stresses needed to deform at high strain rates. It may be due to strain rate sensitivity of epoxy or may be due to different characteristics of bonds between the fibres and the matrix.

The main object of the present work is to develop a facility of Kolsky technique in the Mechanical Engineering Department of Indian Institute of Technology, Kanpur. This includes design, fabrication and installation of a 20 mm bore Air-gun to be powered by compressed Nitrogen. The gun is fired with the help of a control panel such that the Nitrogen gas is released quickly through the barrel. It also includes design of other accessories such as strain gauges, triggering device, low rise time circuits for strain gauges.

The Kolsky bar setup is to be used to determine the dynamic stress-strain curve of epoxy, which is very commonly used as matrix material of composites. The outline of the thesis is as follows: theoretical formulation is described in Chapter-2; experimental techniques is given in Chapter-3; results and discussion are described in Chapter-4; concluding remarks are made in Chapter-5.

CHAPTER - II

THEORETICAL FORMULATION

Kolsky pressure bar technique is based on the theory of elastic wave-propagation in circular bars. When a shock load is applied to an end of an elastic bar, the bar works like a wave guide. The shock wave travels with velocity $\sqrt{E/\rho}$, where E and ρ are Young's Modulus and density of the bar material. The state of stress in the bar is uniaxial which means there is only one non-zero component of stress and it remains uniform across the thickness of the specimen. When a thin specimen is compressed between two elastic bars, its ends move with different velocities and therefore, the specimen deforms. Further more, as the shock front enters the short specimen, it reverberates and makes the stress more or less uniform in a short time. Kolsky showed that by measurement of stress waves alone in the two elastic bars, the entire information about stress, strain rate and strain in the specimen can be obtained. Kolsky pressure bar technique is schematically shown in Fig. 1 . The apparatus essentially consists of two long and circular bars generally known as Input and Output bars. They are identical in cross-section and chosen such that they always remain elastic. A short piece of specimen is sandwiched between the two bars. The specimen is subjected to a compressive loading,when another bar, the striker, impacts the other end of the input bar. The striker bar is accelerated by an air gun.

The input and output bars act as a means of loading the specimen and also as transducers to measure the stress levels. The strain gauges mounted on the bars give the stress history. Stress wave-propagation in the bars are shown conveniently through a time-distance diagram of the Fig. 2. Distance x is chosen along horizontal axis, while time t is chosen along the vertical axis. For better visualization the striker, input and output bars along with a specimen have been drawn above the t-x diagram. Time t is measured from the instant the front end of the striker touches the input bar.

At the instant of impact, compressive stress waves start propagating in the input bar as well as in the striker with the sound velocity. Stress σ and particle velocity v , are governed by conservation of momentum equations, strain, displacement and constitutive relations. For a simple case of linear elastic material, the governing equations are Hyperbolic. Simple relations are obtained along characteristic directions having slopes + C and − C. The relations along the characteristic are

$$d\sigma - \rho C\, dv = 0 \quad \text{along} + C \text{ characteristic}$$

$$d\sigma + \rho C\, dv = 0 \quad \text{along} - C \text{ characteristic.}$$

The product ρC plays an very important role, because it relates stress with particle velocity and is generally known as acoustic inpedence. State of stress at the impact interface between the striker and the input bar is obtained by writing the jump relations between points 1, 2 and 3. Noting that for the striker just before the impact, stress

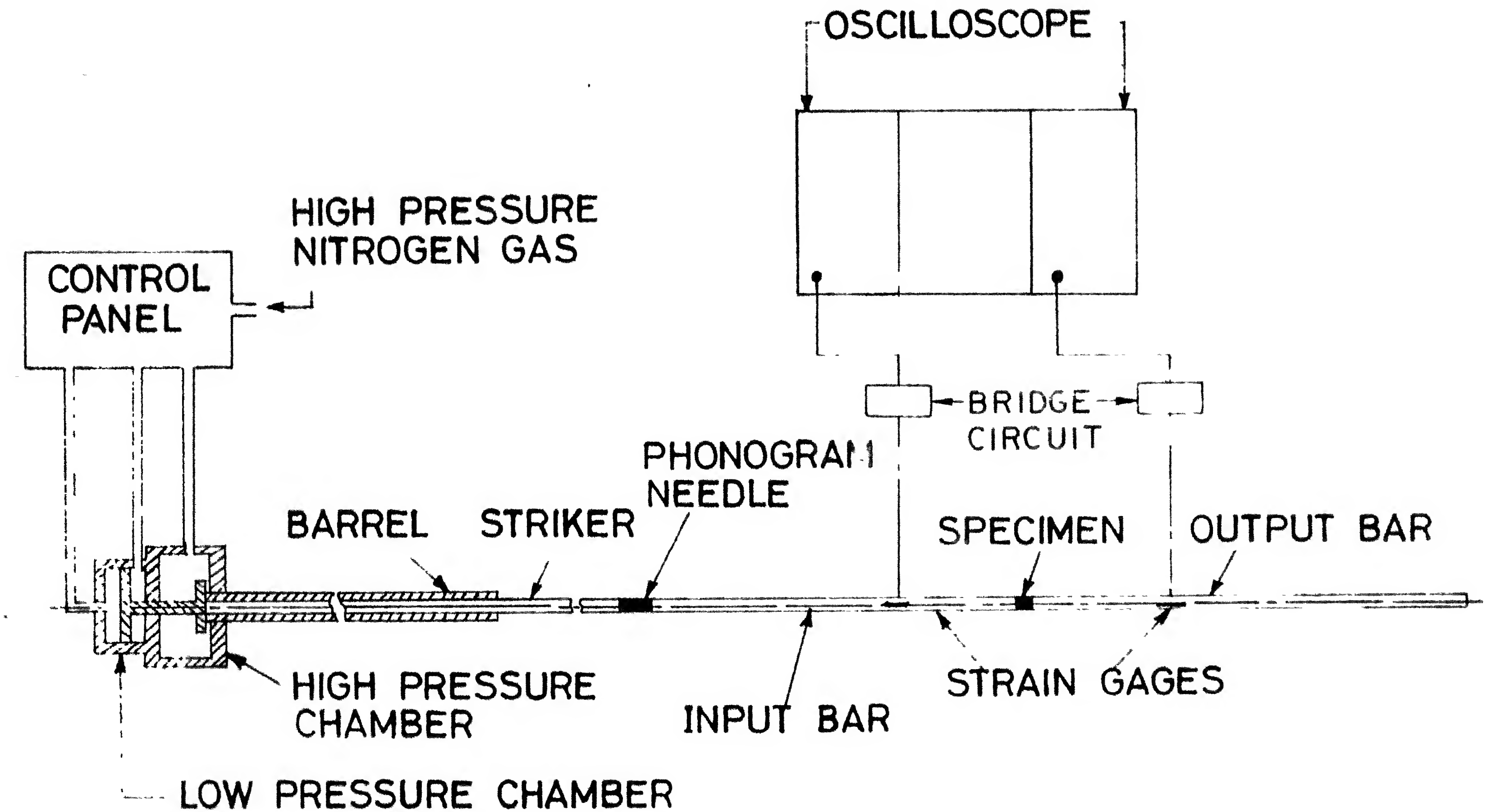


Fig. 1 Schematic diagram of Kolsky bar set-up

$\sigma = 0$ and particle velocity v is equal to the velocity V, one obtains

$$\sigma_1 - \rho c\ v_1 = \sigma_2 - \rho c\ v_2$$
$$= 0 - \rho c\ V \qquad (1)$$

Relation along the characteristic 1 - 3 is

$$\sigma_1 + \rho c\ v_1 = \sigma_3 + \rho c\ v_3$$
$$= 0 \qquad (2)$$

because stress and particle velocity of the input bar at t = 0 are zero. Solving equations 1 and 2 one obtains

$$\sigma_1 = -\frac{\rho c\ V}{2} \qquad (3)$$

and $$v_1 = V/2 \qquad (4)$$

The negative sign signifies that the stress is compressive. This state of stress at the impact interface between the striker and the input bar is unchanged until a wavefront arrives after being reflected from the end of one of the two bars. Since the striker bar is shorter in length the compressive wavefront encounters its free surface ($\sigma = 0$) and is reflected back into the bar to reach the impact face shown by characteristic B-C in the figure. Particle velocity at the point 11 is found by the equations

$$\sigma_{11} + \rho c\ v_{11} = \sigma_1 + \rho c\ v_1 \qquad (5)$$

or, $$0 + \rho c\ v_{11} = \frac{-\rho c\ V}{2} + \frac{\rho c\ V}{2}$$

or, $$v_{11} = 0$$

which means, the striker attains zero velocity and zero stress once the reflected pulse wave front sweeps the striker. Consequently, after

twice the propagation time in the striker ($2l_s/C$) the interface at x = 0 no longer has any compressive stress. The compression which acts on the impact face for the time interval $2l_s/C$ takes the shape of a compressive pulse in the input bar. The boundary conditions on the input bar should generate a square pulse with small rise time, $\tau = \frac{5d}{C}$, where d is the diameter of the bar.

The pulse propagates with the speed of sound/C in the input bar till it hits the specimen. Due to difference in acoustic impedences, part of the pulse is reflected into the input bar and rest is transmitted to the output bar. Within the specimen there are several reverberations of the stress waves between the two elastic and hard rods. Figure 3 shows relationship between stress and particle velocity for both the pressure bars and the specimen. The line BC corresponds to the input bar and has its slope equal to $-\rho C$. The line AB corresponds the output bar and has a slope equal to $+\rho C$. Since the Kolsky pressure bars are chosen hard (high acoustic impedence) in comparision to a specimen, the slope of the line AD, which represents the acoustic impedence of the specimen is smaller as shown in the figure. In fact, when the incident pulse reaches the interface of the input bar with the specimen, the state of stress is given by point D. Similarly when the wavefront reaches the rear end of the specimen the state of stress is given by the point E. The reverberation, continue till the final stress level is reached. At higher stress level, the acoustic impedence ρC is still smaller due to its plastic deformation and the slope of line KL is much lower in

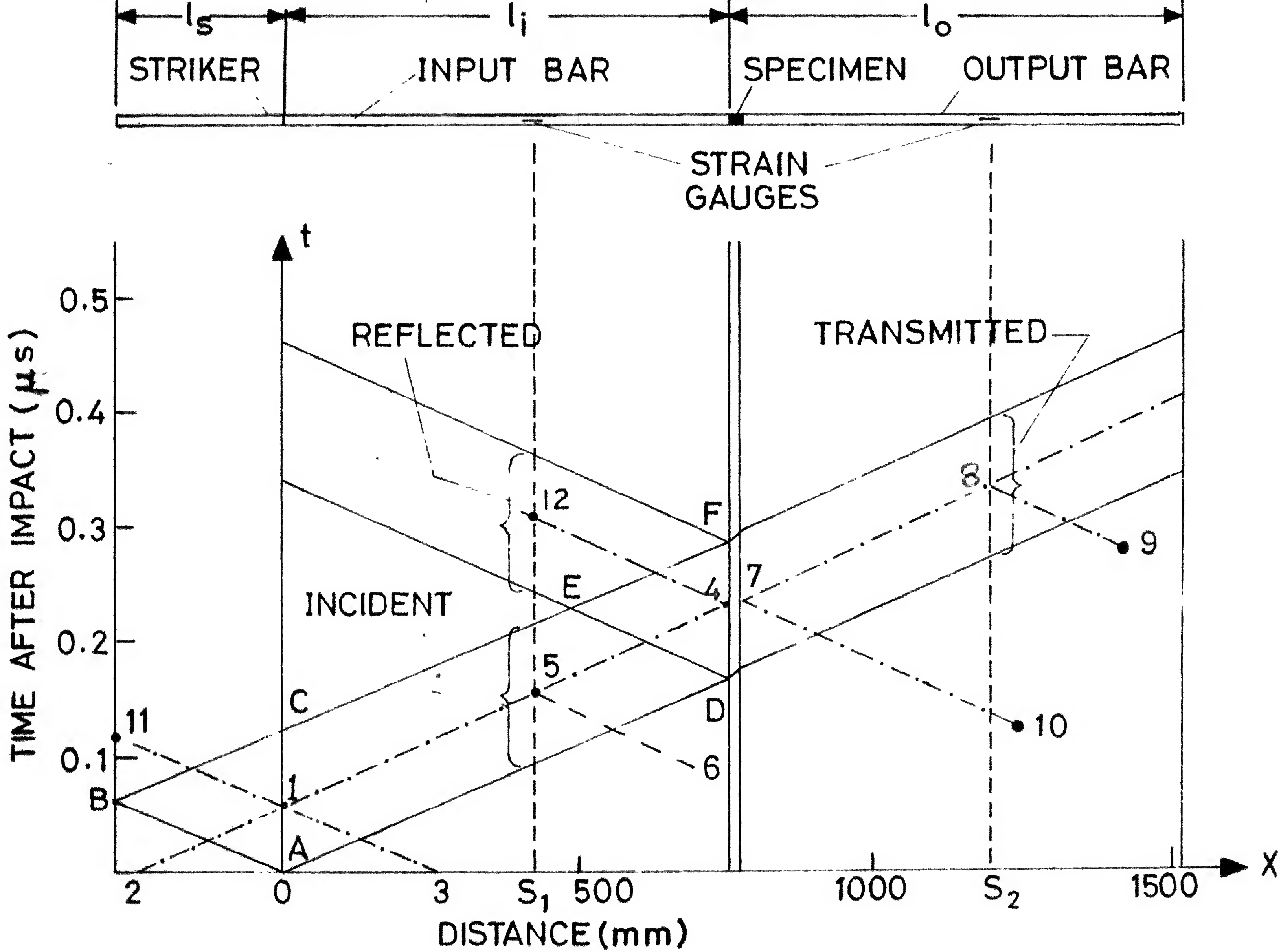


Fig. 2 Time - distance diagram

comparison to that of the line AD. Therefore the stress variation within the specimen is small and one can even assume it to be uniform along the length.

Stresses of the incident and reflected pulse are recorded by the strain gauge S_1 (figure 2) and the stress level of transmitted pulse is recorded by the strain gauges S_2. The recorded information is employed to evaluate stresses and particle velocities at point 4 and 7.

Relations along characteristics 4 - 5 and 5 - 6 are

$$\sigma_4 - \rho c\, v_4 = \sigma_5 - \rho c\, v_5$$

$$\sigma_5 + \rho c\, v_5 = 0$$

Eliminating v_5 one obtains

$$\sigma_4 - \rho c\, v_4 = 2\, \sigma_5 \tag{6}$$

Similarly, relations along characteristic 4 - 12 and 12 - 13 are

$$\sigma_4 + \rho c\, v_4 = \sigma_{12} + \rho c\, v_{12}$$

$$\sigma_{12} - \rho c\, v_{12} = 0$$

Again eliminating v_{12} from these two equations

$$\sigma_4 + \rho c\, v_4 = 2\, \sigma_{12} \tag{7}$$

Equations 6 and 7 yield

$$\sigma_4 = \sigma_5 + \sigma_{12} \tag{8}$$

and $$v_4 = -\frac{\sigma_5 - \sigma_{12}}{\rho c} \tag{9}$$

Similar method is adopted to obtain σ_7 and v_7 interms of measured stress σ_8. Characteristic equation along 7 - 8, 7 - 10 and 8 - 9 are

$$\sigma_7 - \rho c\, v_7 = \sigma_8 - \rho c\, v_8 \tag{10}$$

$$\sigma_7 + \rho c\, v_7 = \sigma_{10} + \rho c\, v_{10} = 0 \tag{11}$$

$$\sigma_8 + \rho c\, v_8 = \sigma_9 + \rho c\, v_9 = 0 \tag{12}$$

By solving the above equations one obtain

$$\sigma_7 = \sigma_8 \tag{13}$$

$$v_7 = \frac{\sigma_8}{\rho c} \tag{14}$$

Since the equations 9 and 14 express particle velocities of the end faces of the specimen, the strain rate is given by the following expression.

$$\dot{\epsilon} = \frac{v_7 - v_4}{h}$$

or, $$\dot{\epsilon} = \frac{\sigma_5 - \sigma_8 - \sigma_{12}}{\rho C h} \tag{15}$$

And the average stress in the specimen is

$$\bar{\sigma} = \frac{\sigma_4 + \sigma_7}{2}$$

or, $$\bar{\sigma} = \frac{\sigma_5 + \sigma_{12} + \sigma_8}{2} \tag{16}$$

If symbols I, R and T are employed to represent incident, reflected and transmitted pulses, the above two important equation changes

to

$$\dot{\epsilon} = \frac{\sigma_I - \sigma_T - \sigma_R}{\rho Ch} \tag{17}$$

$$\bar{\sigma} = \frac{\sigma_I + \sigma_T + \sigma_R}{2} \tag{18}$$

The strain is determined by integrating the equation 17 as shown in the following equation

$$\epsilon = \int_0^t \frac{(\sigma_I - \sigma_T - \sigma_R)\,dt}{\rho Ch} \tag{19}$$

For many meterials the sound velocity C is small at a stress level where the material is being deformed plastically. Then the accoustic impedence is also small and the equations 15 and 16 can be simplified by assuming $\sigma_4 = \sigma_7$

Equations 8 and 10 give

$$\sigma_{12} = \sigma_8 - \sigma_5$$

Substituting these in equations 15 and 16 to obtain

$$\dot{\epsilon} = \frac{2\,(\sigma_5 - \sigma_8)}{\rho Ch} = \frac{2\,(\sigma_I - \sigma_T)}{\rho Ch} \tag{20}$$

The average stress simplifies to

$$\bar{\sigma} = \sigma_8 = \sigma_T \tag{21}$$

In this particular case the strain gauge on the output bar directly gives stress in the specimen.

The technique is simple and direct but has its own limitations. In the first few reverberations in the specimen stress level is low and

non-uniform and therefore expressions used for data processing are not rigorous. As a matter of fact there is always an uncertainty of what happens at low strains.

Another limitation is that at extremely high strain rates say of the order of 1000 sec^{-1}, stress wave propagation in the bars are very highly influenced by the lateral surfaces which are free. So any loading of a specimen will have to depend on the release of hoop and radial stresses with the help of lateral free surfaces. Thus the process involves a time constant and the specimen cannot be deformed at very high strain rates. However, recently attempts have been made by constraining the lateral surfaces to obtain strain rates of the order of 10^4 to 10^5 sec^{-1}.

Whatever the shortcomings are of the Kolsky bar setup, it is still the only one known so far. No matter how fast a specimen is pulled in a conventional machine like Instron, the strain rate is several orders less than the typical strain rate of $10^2 - 10^3$ sec^{-1} through Kolsky bars.

CHAPTER - III

EXPERIMENTAL TECHNIQUE

Kolsky pressure bar apparatus is shown schematically in Fig.1 and the actual setup is shown in Fig.7. The apparatus mainly consist of an Air Gun, two long elastic mild steel bars called Input and Output bars, Striker bar, Strain gauges and their bridge circuit, Phonogram needle and a Taktronix 7633 storage type oscilloscope. Each of these is discussed under respective titles.

Air Gun:

The cross-section of air-gun and its controls is schematically shown in Fig. 4. The Air-gun mainly consists of a breech and barrel assembly. The barrel assembly which is connected to the breech is a steel tube of 20 mm. internal diameter which houses a striker of 19.7 mm. diameter. The breech assembly consist of two pressure chambers and a piston assembly. The right end of the piston assembly carries a conical nylon ring which fits into the matching conical end of the barrel. The left end of the piston assembly moves in the low pressure chamber and its movement is regulated by the pressure on either side of the piston in the low pressure chamber. The valves V_1 and V_2 are used to pressurise the chambers, while valves D_1, D_2, D_3 are used to release the pressure. For firing the gun, the high pressure chamber is first sealed by moving the piston assembly to the right by pressurising the rear end of the

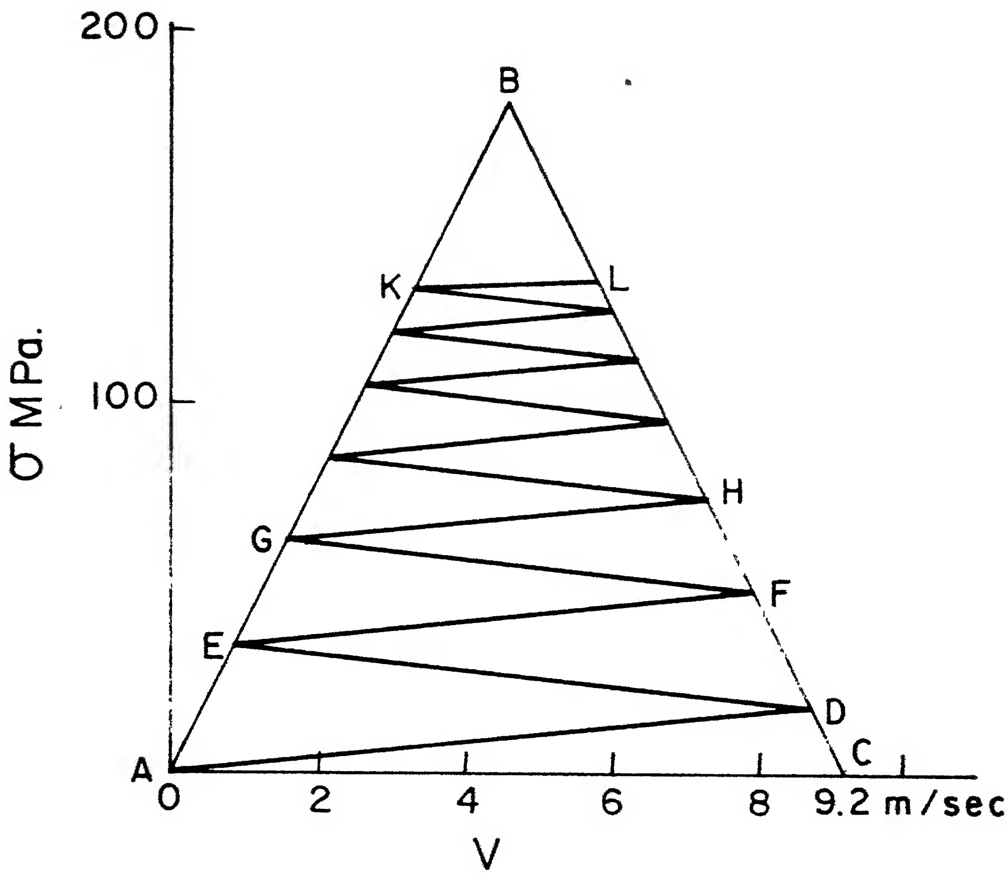


Fig. 3 Stress vs. particle velocity in the specimen

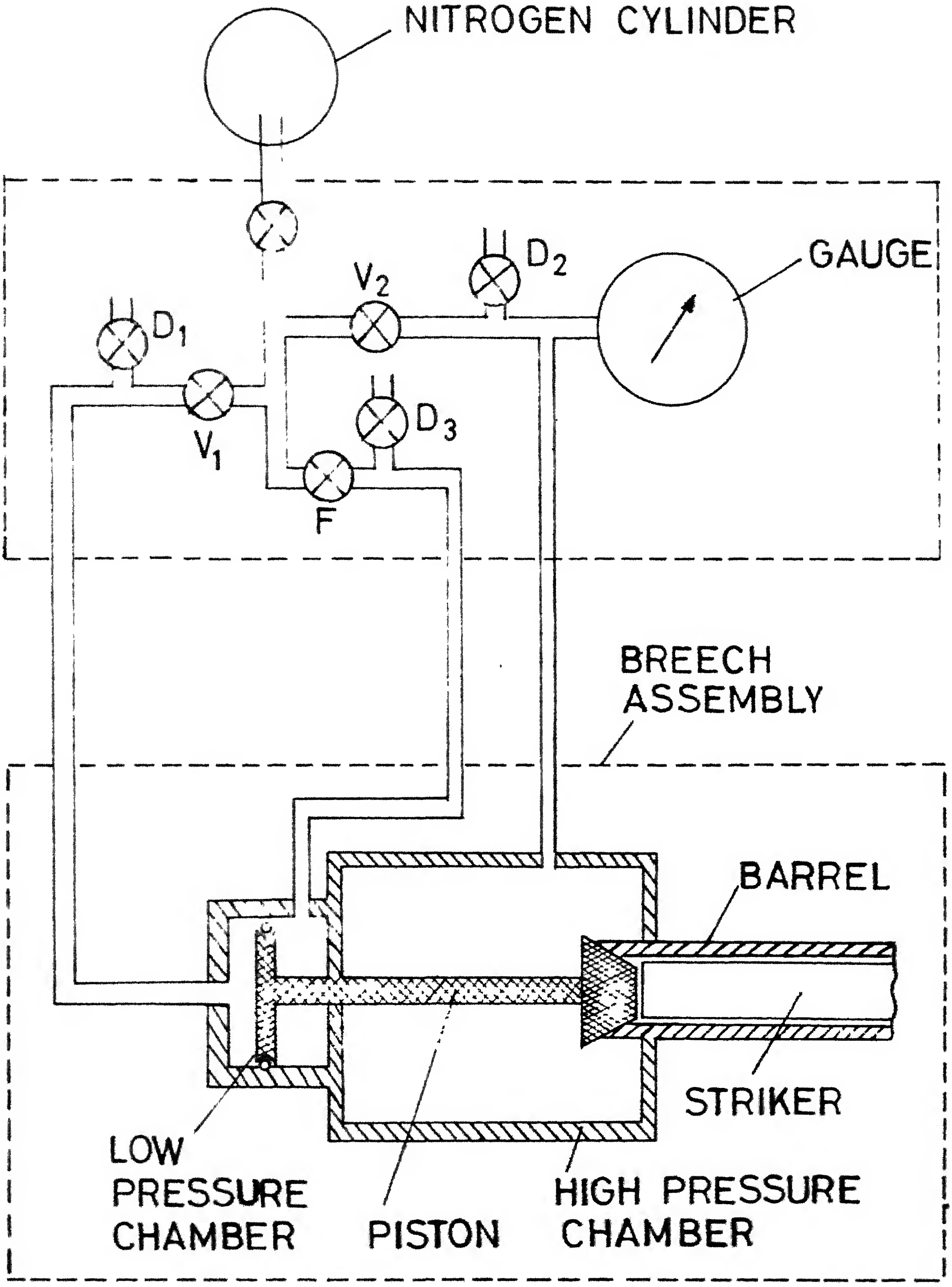


Fig.4 Schematic diagram of breech assembly and control panel

piston in low pressure chamber. Now high pressure chamber is pressurised by opening valve V_2. Then the pressure in the low pressure chamber is released. The pressure in the high pressure chamber is sufficient to keep the piston assembly in position and hence keep the high pressure chamber sealed. The front end of the low pressure chamber is pressurised by operating the lever of a fast opening valve F, to move the piston assembly to the left at high speed. This unseals the barrel and the gas in the high pressure chamber rushes into the barrel to accelerate the striker. The breech assembly is designed to withstand 10 MPa gas pressure.

Kolsky Pressure Bars and Striker:

Kolsky bars consist of two identical bars of same diameter (20.3 mm) and length (850 mm) with their faces machined perfectly flat; the faces are further polished by fine emery papers and are buffed using a felt cloth to obtain mirror like polish. Both the bars and the striker are made of mild steel. The bars are aligned accurately along the axis of the gun barrel. In order to minimize the effect of any misalignment, the front face of the striker is machined into a spherical shape with a radius equal to fifteen times that of the bar. This ensures that a misaligned striker will always make a point contact on the flat face of the input bar. Although the rounded front face of the striker bar gives a slowly rising ramp type of shock front, it does not cause any problem as a shock in the bar has its own rise time. For the 20 mm bars the rise time is 20 μsec., which is large enough to absorb irregularities due to the rounded end of the striker.

Strain Gauges:

The stress level of the pulses are monitored through strain gauges. The strain gauges on the input bar cannot be glued close to the interface end (where the specimen is placed) because front end of the reflected pulse is superimposed on the tail of the incident pulse. For a striker of 285 mm length strain gauges are placed at 425 mm from the interface end. By the time the reflected pulse reaches the strain gauges the incident pulse has already crossed the gauge and thus pulses are separately recorded. Two strain gauges are mounted diametrically opposite on each bar.

In the output bar, the strain gauges are glued again at 425 mm from the interface. Because the strain gauges are placed at equal distance from the interface, reflected pulse in the input bar and the transmitted pulse in the output bar reach the strain gauges at the same instant. Then the recording can be made on one oscilloscope by chopping the beam. In addition, the relation between the reflected pulse and the transmitted pulse can be easily seen for the entire duration.

Strain Gauge Circuit:

In this kind of experiment, stress waves are mainly longitudinal type. But due to eccentric impact between the striker and the input bar, flexural waves may generate. Although the net effect of the flexural waves on average stress a strain is negligible, one has to be careful in cancelling the effect while measuring the stress through strain

gauges. The wheatstone bridge circuit is found to be useful for measuring dynamic strains. Two strain gauges are glued diametrically opposite on a pressure bar and they form the opposite arm R_2 and R_4 of the wheatstone bridge circuit as shown in the figure 5. Each gauge is 3 mm long and is of 120 Ω resistance.

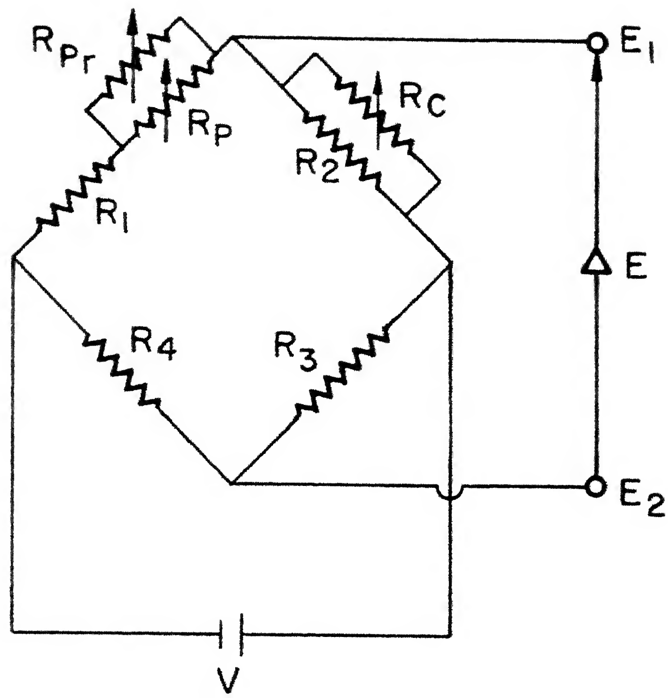
Fig. 5 shows the strain gauge bridge circuit. Resistance R_3 of the bridge circuit corresponds to a dummy strain gauge mounted on a small metal rod of same diameter as that of the pressure bars. It is identical to active gauges in size and resistance. Resistance R_1 corresponds to a constant resistor of 100 Ω connected in series with a 50 potentiometer. Another 2000 Ω precession potentiometer is connected in parallel to the 50 Ω potentiometer. The 50 Ω and 2000 Ω potentiometer provides coarse and fine balances respectively.

Another resistor of high resistance R_c along with a shorting push button is connected in parallel with the strain gauge R_2. The calibration resistor R_c is of variable type. When the push button is shorted the resistance accross the gauge R_2 changes, which in turn gives an output on the oscilloscope. Thus it gives a direct calibration relation between the resistance change of the gauge and voltage deflection V_c on the oscilloscope.

Before every measurement a null point is obtained by controlling the potentiometers.

Then $\Delta E = 0$

or $E_1 = E_2$



R_1 = 100 Ω Resistance

R_2 = 120 Ω Active strain gauge

R_3 = 120 Ω Dummy strain gauge

R_4 = 120 Ω Active strain gauge

R_P = 50 Ω Potentiometer

R_{Pr} = 2 K Ω Precession potentiometer

R_C = 50 K Ω Variable type calibration resitance

V = 9 V D.C. Battery

ΔE = Bridge voltage

Fig. 5 Bridge circuit

or, $$\frac{R_2 V}{R_1 + R_2} = \frac{R_3 V}{R_3 + R_4}$$

or, $$R_1 R_3 = R_2 R_4 = R^2 \quad \text{since } R_2 = R_4 = R$$

When the calibration resistor R_c is connected in parallel to strain gauge R_2 by pushing the push button S, the overall resistance changes by ΔR_2.

Then $$R_{2e} = \frac{R_2 R_c}{R_2 + R_c}$$

where R_{2e} is the equivalent resistance, and

$$\frac{\Delta R_2}{R_2} = \frac{R_{2e} - R_2}{R_2}$$ which gives

$$\frac{\Delta R_2}{R_2} = \frac{- R_2}{R_2 + R_c}$$

The gauge factor S_g of the strain gauges is defined by

$$S_g = \frac{\Delta R_2 / R_2}{\epsilon}$$

where S_g is the strain in the gauge.

Therefore the strain induced ϵ_c due to change in R_2.

$$\epsilon_c = \frac{- R_2}{S_g (R_2 + R_c)}$$

Corresponding to this strain calibration voltage V_c is directly read from the oscilloscope screen. Since the stress pulses are monitored through two gauges the voltage output is double for the same strain.

Triggering Mechanism:

The oscilloscope which records the output from the strain gauges is used on a single sweep mode and it should be triggered before the wave front reaches the strain gauges. The scope is triggered by a phonogram needle clamped to the input bar with the help of rubber bands as shown in figure 9. It is placed close to the striking end of the input bar so that its output can trigger the oscilloscope before the wave front reaches the strain gauges. The needle remains normal to the surface such that its tip touches the bar. A stress pulse deflects the needle to activate inbuilt piezo electric crystal. The electric signal from the crystal is large enough to trigger the oscilloscope when the signal is fed to the external triggering terminal.

Oscilloscope:

Tektronix 7633 oscilloscope is used for the measurements. This is a storage type oscilloscope capable of storing the signals at a fast writting speed. The feature is very useful to record transient type of signals. The oscilloscope can take two vertical plugins and therefore two signals can be recorded by chopping the beam. The Input bar strains are measured by ordinary preamplifier at 5 mV/division sensitivity, while output bar strains are mesured by comparatively more sensitive differential comparator plug in, with a vertical sensitivity of 2 mV/division.

The signals from the wheatstone bridges are of very low voltage (1 - 10 mV) and therefore causes problem while measuring them.

This is mainly due to noise created by line voltages, radio signals and most often induced voltages in the circuits. In fact the amplitude of the noise is more than the signal itself. The remedy for the problem is to use good quality shielded wires with B and C type connectors. The noise is further reduced by grounding the Kolsky pressure bars and the box containing the bridge circuit.

Specimen and Its Preparation:

In this study epoxy specimen are employed. The raw material was bought from Ciba CY 230 type resin and HY-951 type hardner are used. A special mould shown in Fig. 6 is used for preparation of the specimen. The inner surface of the mould is prepared by applying a thin layer of greese properly. Then a well stirred epoxy resin and 10 % hardner soln. is poured into the mould. The mould was placed in a vacuum chamber to remove dissolved air bubbles in the solution. This mould is taken out and a pressure of about 0.5MPa is applied through a plunger and dead weights. The specimen are cured at room temperature for 5 days. The cast epoxy rod is machined accurately to 18.5 mm outside diameter and 8 mm inside diameter and to a length of 7 mm. The two faces of the specimen are machined exactly parallel and perfectly flat. They are polished by very fine emery paper and then buffed by felt cloth.

The specimen is much shorter than the diameter of the bars unlike in case of metals where length is generally chosen equal to the diameter of the bars. The modification is necessary due to the fact

that the sound velocity in epoxy is much smaller than in metals. If the specimen is chosen large there will be only few reverberations within the specimen and the stress will not be uniform.

Another problem arises when the length of the specimen is small. The free lateral surfaces are now far away from the bulk of the material and the state of uniaxial stress is not achieved. Infact, material feels lateral stresses (radial and hoop stresses). In order to minimise such undesirable effects 8 mm diameter hole is provided. The free surfaces of the hole releases the lateral stresses.

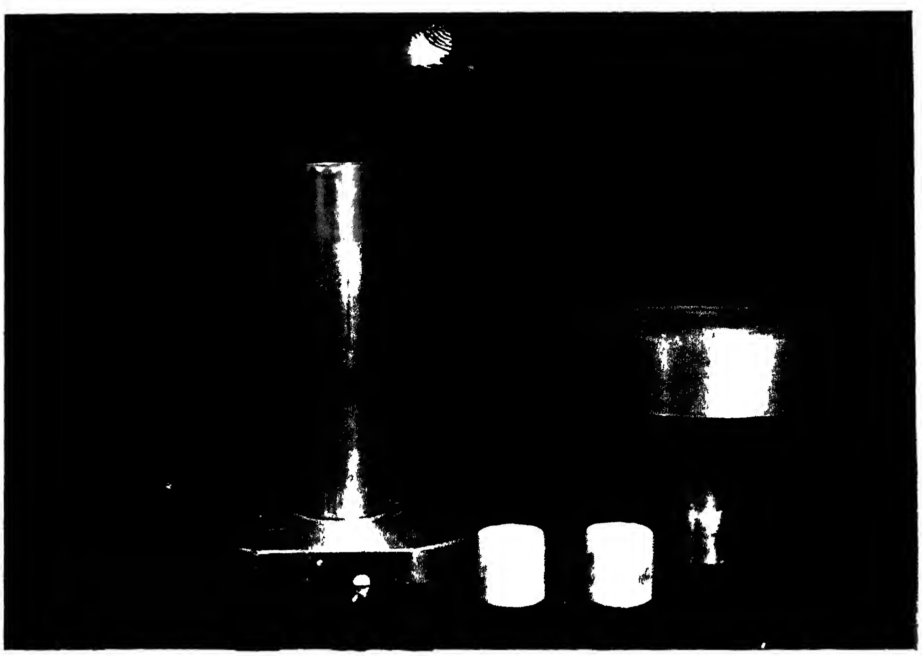


FIG. 6 : MOUID TO PREPARE SPECIMEN
ALONG WITH PLUNGER

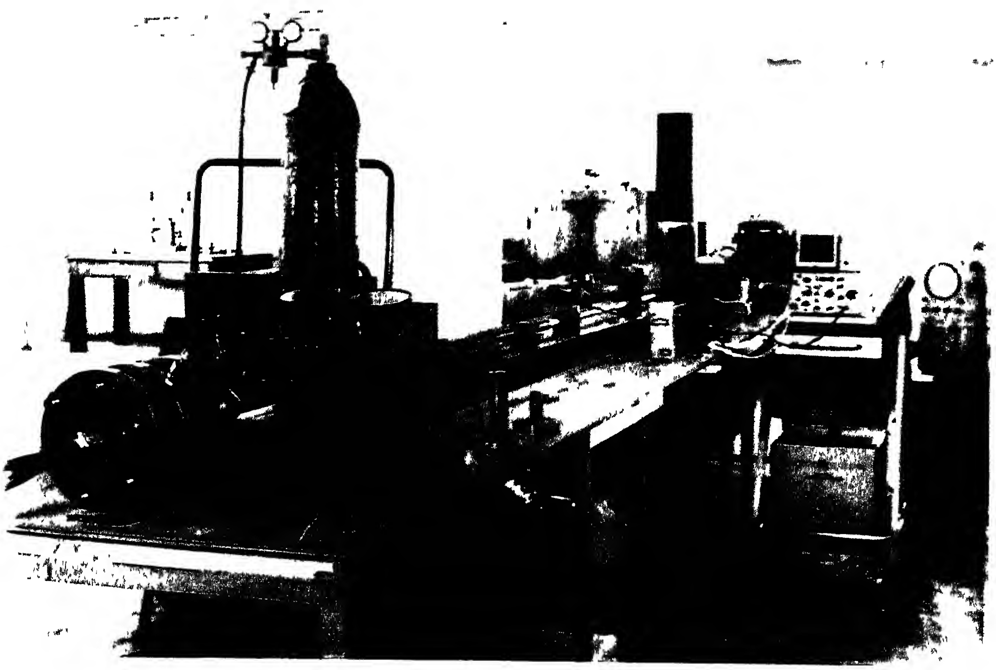


FIG. 7 : KOLSKY PRESSURE BAR APPARATUS

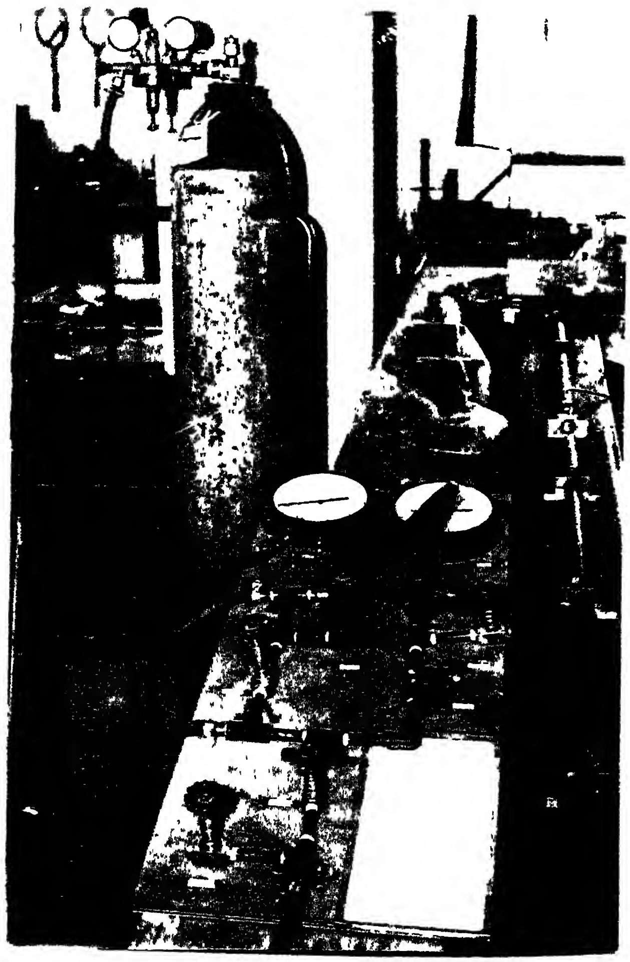


FIG. 8 : FIRING CONTROL PANEL

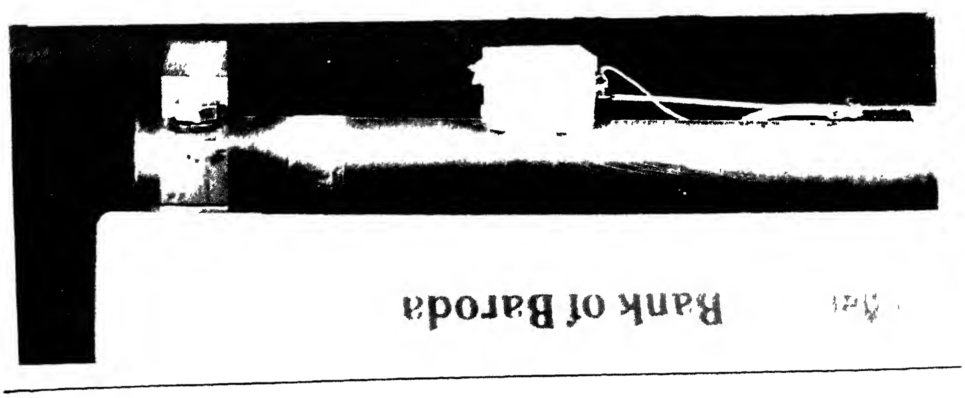


FIG. 9 : PHONOGRAM NEEDLE ATTACHED TO
THE INPUT BAR FOR TRIGGERING
AN OSCILLOSCOPE

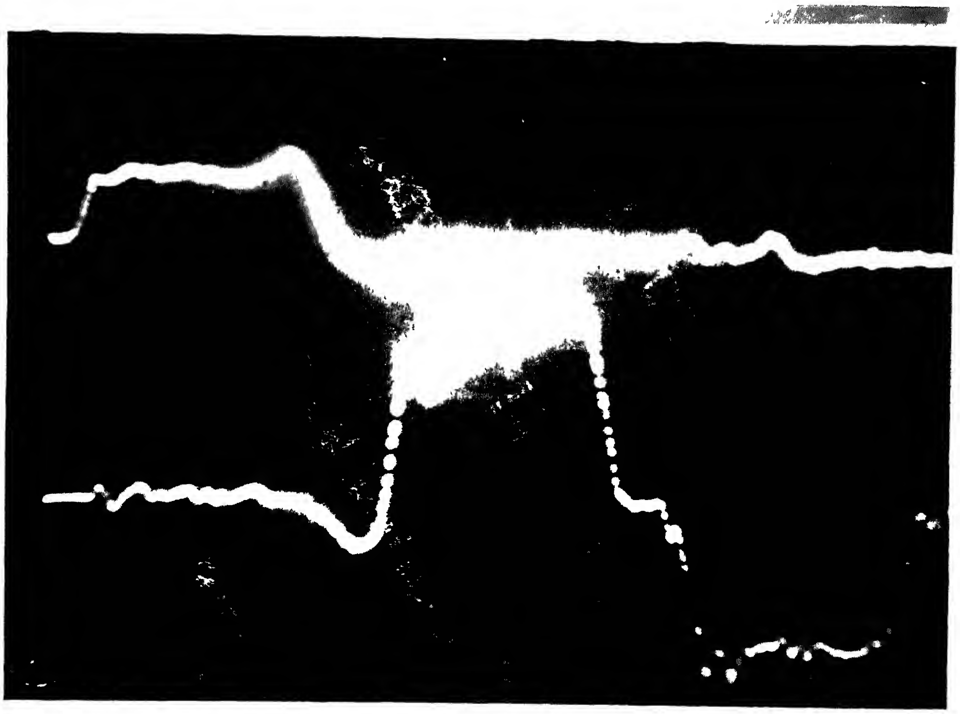


FIG. 10 : OSCILLOSCOPE DISPLAY WITHOUT
ANY SPECIMEN BETWEEN INPUT
AND OUTPUT BARS
HORIZONTAL SWEEP RATE – 50 MICROSECOND/DIV.
VERTICAL SENSITIVITY:
UPPER TRACE – 5 MV/DIVISION
LOWER TRACE – 2 MV/DIVISION

matches with the observed value within five percent. Further more, the top portion of the incident pulse is not a perfect straight line as predicted by the theory. The undulations is caused by the superimposition of noise on the pulse.

Although the calibration resistance R_c does provide a relation between the oscilloscope voltage output and strain, velocity of the striker is measured directly to check this calibration relation. The direct velocity is measured through charged pins as described in detail in Appendix: A. The stress level of the incident pulse is measured to be 168 MPa while the stress pulse magnitude calculated from the velocity of the striker is 160 MPa. The difference is five percent mainly due to the fact that the projectile velocity is not measured very accurately. Thus the entire stress measurement system is found satisfactory. The incident pulse in the input bar is transmitted to the output bar. Since the bars are identical, there is negligible reflection at the interface and therefore shows nothing but noise after the first pulse. The pulse in the output bar is recorded as compression pulse in the lower trace. When the pulse reaches the rear end of the output bar, it is reflected as tensile pulse. This is recorded as second pulse in the lower trace. The tensile pulse is reflected again into the output bar by the interface as compression pulse. The pulse does not propogate into the input bar because of its tensile character.

The experimentally observed traces show all the features predicted by the elastic theory of waves quite well. Thus, one proceeds confidently towards the next step of placing a specimen between the two bars.

Experimental Results on Epoxy Specimen:

Fig. 11 shows the oscilloscope trace of a typical shot (No. 1) when the epoxy specimen is sandwiched between the two pressure bars and the striker bar impacts the input bar. The upper trace corresponds to the input bar signals and the lower trace corresponds to the output bar signals. The input bar signal is recorded at a vertical sensitivity of 5 mv/division while the output bar signal is recorded at 2 mv/division sensitivity. The horizontal sweep rate is 50 μ sec/division. In upper trace the first pulse is the incident pulse of 115 μsec. duration and 248 MPa compressive stress. The second pulse is reflected pulse from the interface of the input bar and the specimen. As discussed in Chapter-II, the reflected pulse is tensile in character and so its polarity is inverted. Its magnitude is large in the beginning when only a small portion of the momentum is transmitted. It decreases as the magnitude of the transmitted pulse increases. The transmitted pulse is recorded in the lower trace. The stress, compressive in nature, rises from zero to the final value of 70 MPa. The unloading part of the pulse is not important for this study.

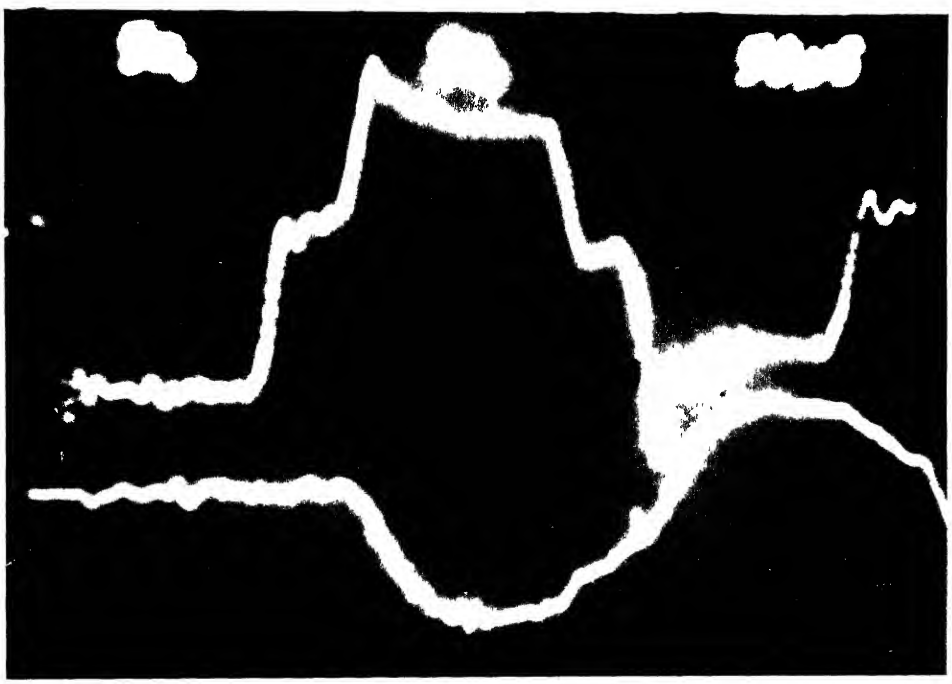


FIG. 11: OSCILLOSCOPE DISPLAY FOR SHOT No.1
HORIZONTAL SWEEP RATE – 50 MICROSECONDS/DIVISION
VERTICAL SENSITIVITY:
UPPER TRACE – 5 MV/DIVISION
LOWER TRACE – 2 MV/DIVISION

The three measured quantities are sufficient to determine average stress and the strain rate of deformation of the epoxy specimen. Equations are modified to the following equations to account for differences in cross-section areas of bars and the specimen. The modified equations are:

$$\sigma_{av} = \frac{A_b}{2A_s}(\sigma_I + \sigma_R + \sigma_T)$$

and

$$\dot{\epsilon} = \frac{(\sigma_I - \sigma_R - \sigma_T)}{\rho c h}$$

$$\epsilon = \int_0^t \dot{\epsilon}\, dt$$

where A_b and A_s are the cross section areas of the bar and the specimen respectively. σ_I, σ_R and σ_T are stress levels of the input, reflected and transmitted pulses respectively. σ_{av} is the average stress within the specimen. $\dot{\epsilon}$ is strain rate, in sec^{-1} and ϵ is average strain in the specimen.

Thus the trace from the photographs provide relation between stress and time and strain rate and time. Average strain is obtained by graphical integration of the strain rate with respect to time. Each photograph of the trace is enlarged to 210 mm X 280 mm size for accurate measurements.

Similar experiments are conducted on the identical specimen but the velocity of the striker is varied by having different nitrogen gas pressure in the breech assembly. Then, the magnitude of the

incident pulse changes which in turn changes the rate of deformation. In fact, there is no direct control on the strain rate. The specimen deform at high strain rate if the load on it is higher. Other three shots (number 2,3, and 4) are tabulated in the Table:1 along with the shot number 1. The traces are shown in Figs. 12,13, 14 respectively. The stress-strain relation for each case is plotted in the Fig. 15. The figure also shows the quasi-static stress-strain curve for the epoxy obtained on Instron Machine. Strain rate in each shot decreases as the strain of the specimen increases. At low strains, curves are shown only by dashed lines because they are questionable. This is due to inherent limitation of Kolsky pressure bar technique which cannot measure strain accurately till the stress in the specimen becomes more or less uniform.

It is evident from the Fig. 15 that epoxy is a very much strain rate sensitive material. As the average strain rate increases from 920/sec. to 1450/sec., the stress-strain curve shifts upwards which means for the same strain, higher stress is required. In fact, at 5% strain, stress required to deform the specimen of the shot-1 at strain rate 1450/sec. is about 100% higher than what is required at quasi-static loading. Even when we compare the two neighbouring curves of shot-2 and 3, the difference in the stress level is as large as 48% at 5% deformation. Therefore, we conclude that strain rate effect on the deformation of epoxy is quite prominent.

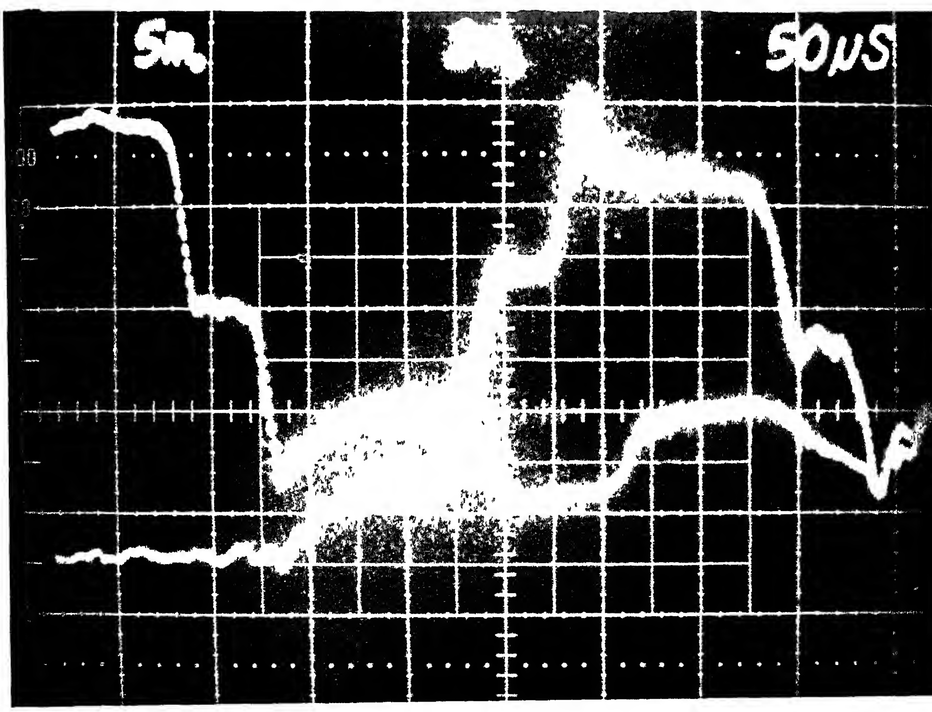


FIG. 12 : OSCILLOSCOPE DISPLAY FOR SHOT NO. 2
HORIZONTAL SWEEP RATE - 50 MICROSECONDS/DIVISION
VERTICAL SENSITIVITY:
UPPER TRACE - 5 MV/DIVISION
LOWER TRACE - 2 MV/DIVISION

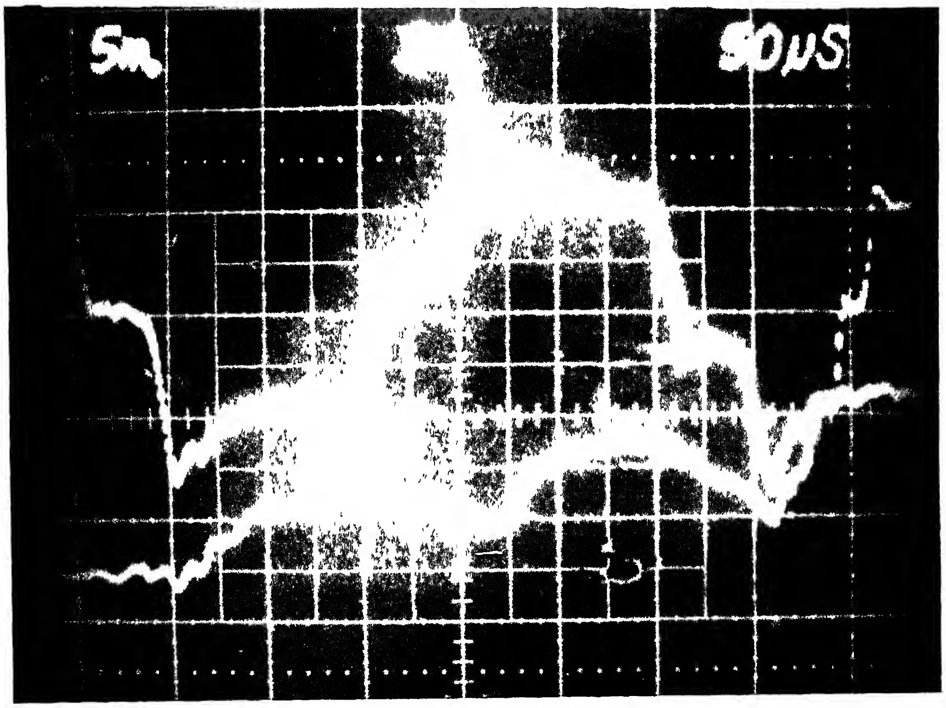


FIG. 13 : OSCILLOSCOPE DISPLAY FOR SHOT NO. 3
HORIZONTAL SWEEP RATE - 50 MICROSECONDS/DIVISION
VERTICAL SENSITIVITY:
UPPER TRACE - 5 MV/DIVISION
LOWER TRACE - 2 MV/DIVISION

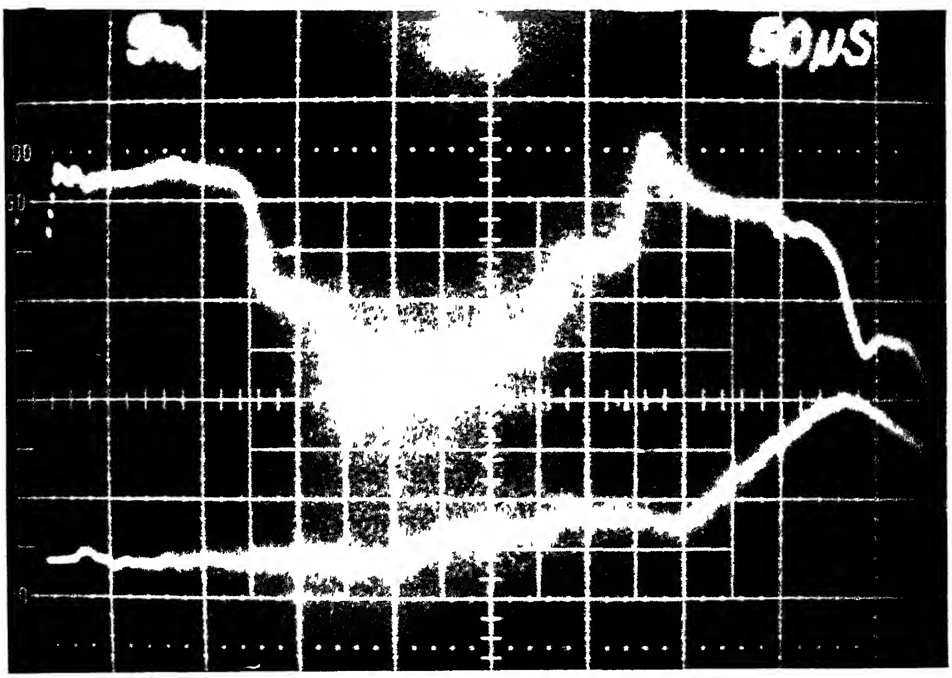


FIG. 14 : OSCILLOSCOPE DISPLAY FOR SHOT NO. 4
HORIZONTAL SWEEP RATE - 50 MICROSECONDS/DIVISION
VERTICAL SENSITIVITY:
UPPER TRACE - 5 MV/DIVISION
LOWER TRACE - 2 MV/DIVISION

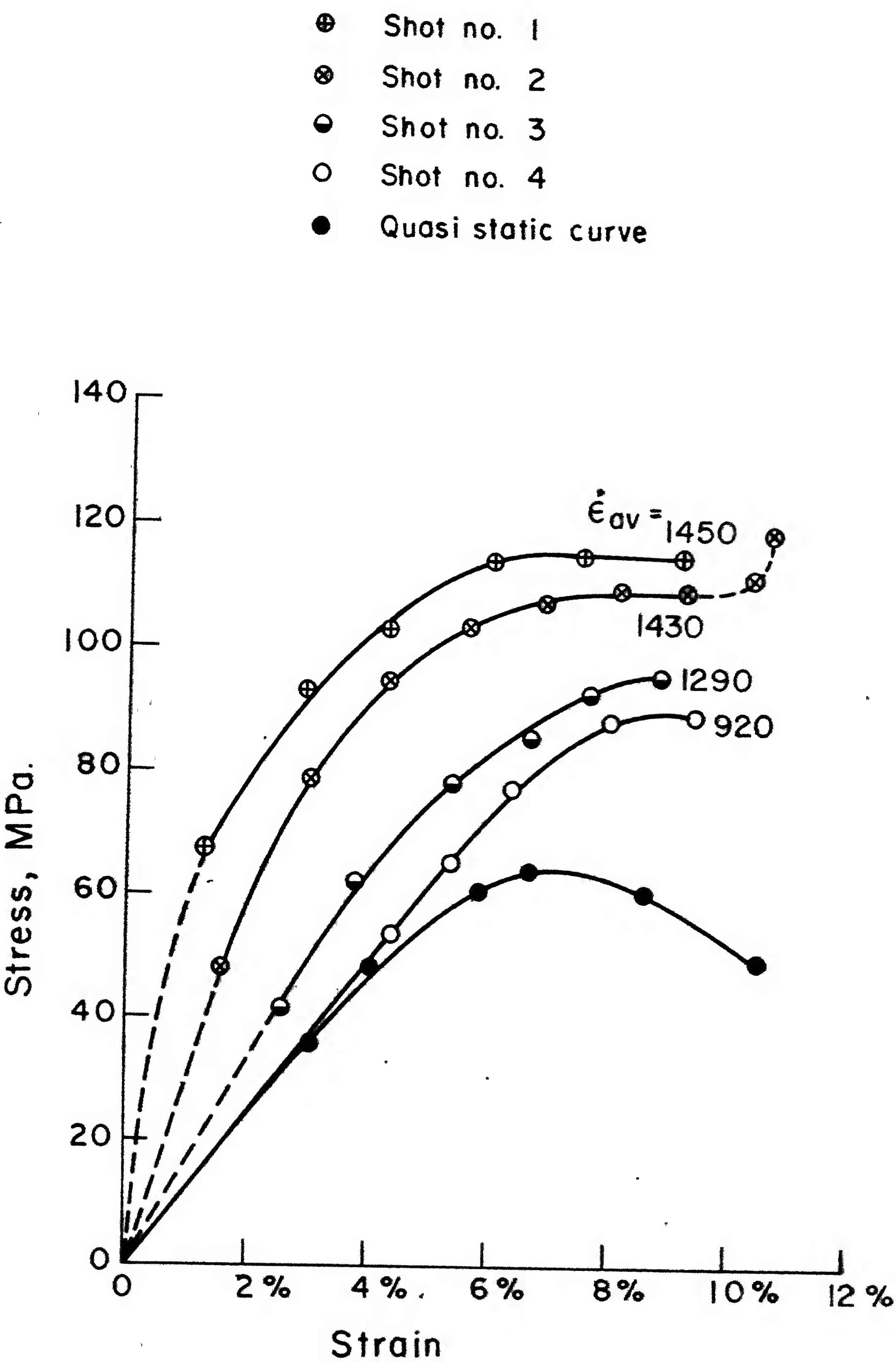


Fig. 15 Stress-strain curves for epoxy specimen at various strain rates

The character of each stress-strain curve is not very different from that of quasi-static curve. In each case, as the strain increases, the slope of the curve decreases. The smaller slope at high stress makes the sound velocity in the specimen smaller, which in turn decreases the acoustic impedence. The result is quite useful for the validity of the Kolsky pressure bar setup, because the low acoustic impedence makes the stress uniform in the specimen.

The curve for quasi-static test between true stress and true strain shows a maximum at about 6% strain. The decrease of stress beyond 6% strain is due to the way the specimen is tested in the Instron machine. The specimen is loaded in displacement controlled mode end therefore it cannot fail in catastrophic manner, even though the load required for further deformation is less. In a load controlled test the specimen would have failed at 6% strain.

At comparatively lower strain rate of the shots 3 and 4 the specimen can take more than 8% strain before they approach maxima. However, at higher strain rate shots 1 and 2 the maximum seems to occur between 7% and 8% of strain.

In short an epoxy specimen can take more strain at high rate of deformation without failure than the maximum failure strain of quasi-static test,but the exact relationship is not clear from the limited experiments of this study.

The lengths of the specimen are measured before and after the test with a vernier calliper as shown in the Table-2. It is clear from the table that the specimen recover their lengths after they are unloaded. Therefore the epoxy behaves like a viscoelastic material even though it is subjected to high stresses at high strain rates.

The transmitted pulse of shot 3 (figure 13) shows an unusual rise towards its tail, which is shown by a dashed line in the figure 15. It is believed that the behaviour does not represent the material property. Rather it may be due to frictional effects at the interfaces between the specimen and the bars. Although care is taken to polish the mating surfaces and applied a good lubricant at the interfaces high friction might have developed at high compressive stresses. Then the specimen is not free to release its stresses in lateral direction. As a result, the specimen no longer deforms in an uniaxial stress mode. In fact, its deformation is mainly governed by the bulk modulus. Because of these reasons, this kind of deformation in shot 3 is not taken into account.

To sum up, the experimental results on Kolsky setup are:

(1) The entire setup works as it was checked on bars with no specimen.

(2) The epoxy is highly rate sensitive.

(3) The epoxy remains viscoelastic at high strain rates.

TABLE - 1

Shot No.	Gun Operating Pressure	Input Stress Pulse Magnitude	Strain Rate sec^{-1}		
			From	To	Average
1	4 Kg/cm^2	248 MPa	1650	1250	1450
2	3.5 Kg/cm^2	240 MPa	1645	1215	1430
3	3 Kg/cm^2	216 MPa	1480	1100	1290
4	2.5 Kg/cm^2	171 MPa	1020	820	920

TABLE - 2

Shot No.	Length in mm	
	Initial	Final
1	7.02	7.02
2	7.0	7.0
3	6.8	6.8
4	7.04	7.04

CHAPTER - V

CONCLUDING REMARKS

The study has been successful in meeting the primary goal which is to setup the complete Kolsky bar apparatus for testing specimen at high strain rate. The task is achieved by designing, fabricating and testing a 20 mm bore Air-gun. Then the pressure bars, strain gauge and its circuits, triggering device are attached and tested. The electrical noise, which caused problem for several months is brought under control by using proper wiring, electrical connectors and grounding. The proper camera attachment is found, to take pictures from the oscilloscope screen. The photographs were enlarged to 210 X 280 mm sizes for better data reduction.

By conducting tests on epoxy specimen, it is shown with a confidence that the entire setup is working well. However certain minor modifications will further improve it. The input bar should be made about 50% longer so that there is ample triggering time available before the pulse reaches the strain gauges. Also, to increase the sensitivity of the strain gauge circuits, strain gauges of higher resistance (say 350 Ω) should be used. Another convenient feature will be to add an integrating circuit to obtain a direct stress strain curve on the screen of an oscilloscope.

Tests on the epoxy specimen exhibit their sensitivity towards strain rate. The stress strain curves shift substantially at the varying strain rates over 900 sec^{-1}. Since the epoxy is quite extensively used in Fibre Reinforced Plastics, results on epoxy are useful from the long term goals of studying dynamic behaviour of composite materials at high strain rates. Some preliminary studies on glass fibre reinforced materials have already demonstrated their dependence on strain rate. By knowing the behaviour of pure epoxy, it is hoped, one may be able to determine what causes the strain rate effect in the composites.

Determination of stress-strain relations at lower strains (upto 2%) are very important from the point of view of the composite materials. Most of the commonly used fibres, such as glass or carbon are at least twenty times more stiff than epoxy and therefore in a composite, epoxy is rarely subjected to such large strains. In this study, the low strain tests could not be conducted mainly due to the reasons:

(1) the striker could not be fired at very low speeds and

(2) low resistance strain gauges were used.

It is,therefore, suggested for future that the gun should be replaced by a vertical tube in which the striker is dropped from a predetermined height. Then the velocity of the striker can be controlled very well.

REFERENCES

1. Baker, L.M., and Hollenbach, R.E., "System For Measuring The Dynamic Properties Of Materials," J. App. Mechanics, Vol. 35, No. 6, (1964) PP. 742-746.

2. Baker, W.E., and Yew, C.H., "Strain- rate Effects In The Propagation Of Torsional Plastic Waves," J. App. Mechanics, Vol. 33, Series E, (1966) PP. 917-923.

3. Davies, E. D.H., and Haunter, S.C., "The Dynamic Compression Testing Of Solids By The Method Of The Split Hopkinson Pressure Bar", J. Mech. and Phys. Of Solids, Vol. 11, (1963) PP. 155-179.

4. Dharan, C.K.H., and Hauser, "Determination Of Stress-strain Characteristics At Very High Strain Rates", Expt. Mechanics, Sept. (1970) PP. 370-375.

5. Duffy, J., Campbell, J.D., and Hawley, R.H., "On The Use Of Torsional Split Hopkinson Bar To Study Rate Effects In 1100-0 Aluminium," J. App. Mech., Vol. 38, Series E, (1971) PP. 83-91.

6. Duffy, J., Hawley, R.H., and Frontz R.A., "The Deformation Of Lead In Torsion At High Strain-rates", J. App. Mech. Trans. ASME, Sept. (1972) PP. 651-656.

7. Hauser, F.E., "Techniques Of Measuring Stress-strain Relations At High Strain Rates", J. Experimental Mechanics, Vol. 6, No.8 (1966) PP. 395-402.

8. Hopkinson, B., "A Method Of Measuring The Pressure Produced In The Deformation Of High Explosives Or By The Impact Of Bullets", Philosophical Trans. Of The Royal Soc., London, Series A, Vol.213, (1914) PP. 437-456.

9. Jahsman, W.E., Re-Examination Of The Kolsky Technique For Measuring Dynamic Material Behaviour", J. App. Mech., Vol. 38, Series E, (1971) PP. 75-82.

10. Johnson, J.E., Wood, D.S., and Clark, D.S., "Dynamic Stress-strain Relations For Annealed 2S Aluminium Under Compression Impact", Trans. ASME, Vol. 25, 1953.

11. Kolsky, H., "An Investigation Of The Mechanical Properties Of Materials At Very High Rates Of Loading", Proceedings Of The Physical Society, Series B, Vol. 62, (1949) PP. 676-700.

12. Lindholm, U.S., "Some Experiments With The Split-Hopkinson Pressure Bar", J. Mech. and Phys. Of Solids, Vol. 12, (1964) PP. 317-335.

13. Lindholm, U.S., and Yeakley, L.M., "High Strain-rate Testing: Tension And Compression", J. Expt. Mech., Jan. (1968) PP. 1-9.

14. Malvern, L.E., "Experimental Studies Of Strain-rate Effects And Plastic Wave Propagation in Annealed Aluminium", Trans. ASME, New York (1965) P. 81-92.

15. Mathew, P., Hastings, W.F., and Oxley, P.L.B., "Machining - A Study In High Strain-rate Plasticity", Inst. Phys., Conf., Ser. No. 47, (1979) Ch. 4, PP. 360-371.

16. Sadao Amijima, Toru Fujii and Soji Shiba, "Impact Strength And Fracture Phenomena Of Fibre Reinforced Plastics", Department Of Mechanical Engg., Doshisha University, Kyoto, Japan.

17. Senseny, P.E., Duffy, J., Hawley, R.H., Experiments on Strain-rate History And Temperature Effects During The Plastic Deformation Of Close Packed Metals", J. App. Mech., Vol. 45, March (1978) PP. 60-66.

18. Wills Mock,Jr. and William H. Holt, "Shock Wave Compression Of An Alumina Filled Epoxy In The Low Giga Pascal Stress Range", J. App. Phy, Vol. 49 (3), March (1978), P.1156-1158.

APPENDIX : A

The direct measurement of striker's velocity is made with the help of five electrically charged pins. Each pair is made of two pins; one is grounded and the other one is charged with 5 volts potential. All the five pins are placed in a line parallel to the axis of the gun and just outside the barrel. Also, the distance between the charged pins of each pair are set at 6 mm. The pins are connected to four time interval measuring counters which can measure time accurately to 1 μ sec. when the steel striker comes out of the barrel, it makes a contact between the two pins of the first pair which in turn starts the first counter. When it contacts the second pair, the first counter stops counting and the second starts counting. The process continue till all the pairs are shorted. Thus time interval is measured for striker to travel 6 mm distance and velocity of the striker is easily determined.